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MATHEMATICAL MODELS FOR STATISTICAL ANALYSIS AND CONTROL OF THE FLOAT PROCESS

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Mathematical models of the process of glass ribbon formation on molten tin have been developed. The efficiency of statistic control of the formation process contributing to the improvement of the quality of the produced glass is demonstrated.

Implementation of quality management systems in sheet glass production implies the use of statistical methods for monitoring and controlling the production process of polished glass. We have developed a method for analysis and control of the regime of glass ribbon formation on molten tin.

The method includes the following phases:

– analysis of the formation process as an object of control for the purpose of selecting an impulse to assess the quality of formation and refine the critical factors;

– development of mathematical models of regime – quality describing the dependence of the parameters of glass ribbon formation quality on variable regime and monitored input parameters;

– development of an algorithm for correcting the regime variables in the glass ribbon formation process depending on the geometrical sizes of the glass ribbon, taking into account variations of controlled disturbances.

We have analyzed the performance of an industrial float-tank with an output of 630 tons/day, the glass ribbon width being 3210 mm (without the edges) and the thickness being 3.2 – 10.0 mm. Statistical data on the formation regime and quality parameters of the glass ribbon produced were monitored during seven months using the PI System.

The quality of glass ribbon formation was evaluated based on the optical distortion visible in the transmitted (the Zebra method) and reflected (the raster method) light based on the nonuniform thickness of the glass and its deviations from planeness or on the "bloom" defect. The specified characteristics and the glass sheet parameters were measured according to the method described in GOST 111–2001. Formation defects (roll imprints, beatenness, adherent crumbs) were not considered, as they were actually absent.

The optical distortions (the Zebra method) were measured at three points across the glass ribbon. The measurement results were statistically correlated and the calculated correlation coefficient was 0.93. This made it possible to estimate optical distortions based on measurement results obtained for one point.

The distortions visible in reflected light (the raster method) were measured at four points across the glass ribbon width. The results of measurements at the ribbon edges were found to be statistically correlated and the calculated correlation coefficient was equal to 0.7. This made it possible to limit oneself to a raster control at three points counted from the right edge of the ribbon along the ribbon movement course.

The nonuniformity of the glass sheet thickness was measured at five points (segments) across the ribbon. The measurement results were statistically correlated and the correlation coefficient was 0.73. Therefore, we limited ourselves to monitoring thickness at three points across the ribbon width counted from the right edge along the ribbon motion.

The deviation from planeness in a glass sheet depends on the temperature of the glass ribbon at the exit from the float-tank and on glass density [1].

The quantity of tin penetrating into the bottom surface of glass was calculated in order to determine the propensity of glass to "blooming" (the "bloom" effect). The amount of tin entrained with the glass (g/m^2 or %) was determined using spectral analysis [2].

To refine the number of models to be developed, the closeness of probability relations between the quality para-

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meters of the glass ribbon was determined. The calculated coefficients of pairwise correlation between the parameters was less than 0.5, which made it possible to develop the models independently of each other.

The process of glass ribbon formation depends on many factors. Assuming that the glass melt penetrating into the float-tank is thermally and chemically homogeneous, we limited ourselves to considering the following factors: the speed of the edge-forming machines; the temperature of tin along the spans of the float-tank; the glass ribbon temperature at the exit from the float-tank; the composition, pressure, and moisture of the protective atmosphere; the temperature in the working channel of the glass-melting furnace; the thickness, width, and velocity of the glass ribbon produced.

To reduce the dimensionality of the problem to be solved, statistical analysis was performed to identify the relationships between the speed of the edge-forming machines and the temperature of tin in the spans of the tank in order to eliminate highly correlated factors from the analysis.

The float-glass tank is equipped with six pairs of edge-forming machines. The rotational speeds of the first and the second pair, as well as that of the third and the fourth pair, are statistically correlated. The calculated correlation coefficients are greater than 0.8, which enabled us to take into account only the rotational speeds of the first and the third pairs of the edge-forming machines.

The temperature of tin in the float-tank is monitored along the left and the right sides over 20 spans. The impulse characterizing the formation temperature regime was selected based on the analysis of the statistical dependence between the temperatures of tin in the spans. Temperatures in adjacent spans are highly statistically correlated. Considering the above, three zones of the float-tank (the 1st, the 12th, and the 20th spans) were chosen to control the temperature of tin. The calculated pairwise correlation coefficients of the temperature of tin in the specified zones do not exceed 0.6, which makes it possible to regard them as independent factors.

For each type of glass ribbon a specific formation regime is selected depending on its geometrical dimensions, the output of the line, and the chemical composition of glass. We analyzed the case where the chemical composition of glass is sufficiently stable and its fluctuations can be neglected.

After the statistical analysis of mutual dependences of the regime variables the following factors were selected to construct regression models: the temperature of tin in the 1st, 12th and 20th span, the repeated heating power, the rotational speeds of the first and third pair of the edge-forming machines, the content (%) of hydrogen and oxygen in the protective atmosphere of the float-tank, and the glass ribbon temperature at the exit from the tank. The monitored disturbing factors were the temperature of the working channel of the glass-melting furnace, the moisture of the protective atmosphere, and the thickness of the ribbon produced.

In developing regression models of the formation process the glass-melting regime was assumed to be stable and, consequently, molten glass delivered for formation was regarded as chemically and thermally homogeneous. These assumptions simplify the development of the models but can affect their accuracy. The possibility of making these assumptions has been confirmed by subsequent research.

Taking into account the stationary regime of the technological line and the limited variation range of the ribbon quality parameters, as well as the results of earlier studies [3], a linear structure was selected for regime – quality models. A consecutive regression analysis procedure was used to refine the model parameters. First, all the above listed factors and disturbances were entered into an initial structure and next, the insignificant variables were consecutively rejected using the Student *t*-criterion. The elimination continued until the accuracy of the model was observed to deteriorate. As a consequence of the analysis performed, the following regression models were obtained:

optical distortions visible in transmitted light (the Zebra method):

$$\mathrm{Zb}(t) = z_0 + z_1 v_{\mathrm{EFM}}(t) + z_2 \theta_1(t) + z_3 \theta_{12}(t) + z_4 \mathrm{C}_{\mathrm{O}_2}(t) + z_5 \delta(t);$$

optical distortions visible in reflected light (the raster method):

$$\mathrm{Ra}(t) = ra_0 + ra_1 \theta_{\mathrm{wc}}(t) - ra_2 \theta_{12}(t) + ra_3 \theta_{20}(t) + ra_4 \theta_{\mathrm{ex}}(t);$$

nonuniformity of the glass ribbon thickness:

$$\mathrm{Nf}(t) = rt_0 - rt_1 v_{\mathrm{EFM}}(t) + rt_2 \theta_{\mathrm{wc}}(t) - rt_3 \theta_1(t) + rt_4 \theta_{12}(t) + rt_5 \delta(t);$$

deviation from planeness (curvature) of the glass sheet:

$$\mathrm{Cur}(t) = -k_1 \delta(t) + k_2 \theta_{\mathrm{ex}}(t) - k_3 \mathrm{Den}(t),$$

the bloom effect:

$$\mathrm{Bl}(t) = b_0 - b_1 \theta_{12}(t) + b_2 \mathrm{C}_{\mathrm{O}_2}(t) - b_3 \theta_{\mathrm{ex}}(t),$$

where $z_0 - z_5$, $ra_0 - ra_4$, $rt_0 - rt_5$, $k_1 - k_3$, $b_0 - b_3$ are the regression coefficients; θ_1, θ_{12}, and θ_{20} are the temperatures of tin in the 1st, 12th, and the 20th span; v_{EFM} is the rotational speed of the first pair of the edge forming machines; $\mathrm{C}_{\mathrm{O}_2}$ is the content (%) of oxygen in the protective atmosphere of the float-tank; θ_{wc} is the temperature in the working channel of the glass-melting furnace; θ_{ex} is the temperature of the glass ribbon at the exit from the float-tank; δ is the thickness of the glass ribbon produced; Den is the glass density; *t* is the time.

Let us demonstrate the efficiency of the developed models for statistical analysis and control of the glass ribbon formation process. The matrix of connectivity of the exit parameters of the formation process with the formation regime and the parameters of the glass ribbon is indicated in Table 1.

TABLE 1

Parameters of glass ribbon formation	Effective factors							
	θ_1	θ_{12}	θ_{20}	θ_{ex}	v_{EFM}	C_{O_2}	δ	θ_{wc}
Optical distortions determined by methods:								
"Zebra"	+	+	0	0	+	+	+	0
Raster	0	–	+	+	0	0	0	+
Nonuniform thickness	–	+	0	0	–	0	+	+
Curvature of glass sheet	0	0	0	+	0	0	–	0
Bloom effect	0	–	0	–	0	+	0	0

Note. "+") direct dependence, "–") inverse dependence; "0") insignificant correlation between the parameter and the factor.

The controlling factors selected from the set of effective factors are the temperature of tin in the 1st, 12th, and 20th spans and the glass ribbon temperature at the exit from the float-tank. The oxygen content in the protective atmosphere is a monitored regime variable. The variations in the thickness of the glass ribbon produced, the rotational speed of the first pair of the edge-forming machines, the temperature fluctuations in the working channel of the glass-melting furnace, and glass density fluctuations create disturbing effects on the formation process.

Control of the process of glass ribbon formation can be regarded as the problem of improving the quality of glass by reducing the amount of tin entrained by the glass produced (the bloom effect). At the same time, certain restrictions are imposed on optical distortion, nonuniform thickness, and deviations from planeness (curvature) of the glass sheet in accordance with the requirements of GOST 111–2001.

In view of the above, the criterion of controlling the formation process can be written in the form of a penalty function [4]:

$$
\begin{gathered}
F = \lambda_1 \,\mathrm{Bl} + \lambda_2 \,|\min((4 - \mathrm{Ra}), 0)| + \\
\lambda_3 \,|\min((-50 + \mathrm{Zb}), 0)| + \lambda_4 \,|\min((0.2 - \mathrm{Nf1}), 0)| + \\
\lambda_5 \,|\min((0.2 - \mathrm{Nf2}), 0)| + \lambda_6 \,|\min((0.025 - \mathrm{Cur}), 0)| + \\
\lambda_7 \max(|215 - (\theta_1 - \theta_{12})| - 7), 0) + \\
\lambda_8 \max(|188 - (\theta_{12} - \theta_{20})| - 8), 0) + \\
\lambda_9 \max(|8.5 - (\theta_{20} - \theta_{ex})| - 5.5), 0) + \\
\lambda_{10} \,|\min((-1 + \mathrm{Bl}), 0)| + \lambda_{11} \,|\min(\mathrm{Ra}, 0)| + \\
\lambda_{12} \,|\min(\mathrm{Nf1}, 0)| + \lambda_{13} \,|\min(\mathrm{Nf2}, 0)| + \lambda_{14} \,|\min(\mathrm{Cur}, 0)|,
\end{gathered}
$$

where $\lambda_1 - \lambda_{14}$ are the penalty coefficients whose values are selected experimentally.

Within the penalty function the summands with the coefficients λ_2 and λ_3 limit the optical distortion values; the summands with λ_4 and λ_5 — the nonuniformity in glass thickness; λ_6 — the deviation from the planeness of glass sheet; $\lambda_7 - \lambda_9$ — the intensity of variation of glass melt temperature in the tank spans; $\lambda_{10} - \lambda_{14}$ — the area of describing the output variables with the regression models. The first summand with λ_1 characterizes the penalty increment as the bloom effect parameter grows.

The problem of controlling the operation of a float-tank consists in selecting the temperature regime for the glass ribbon formation to ensure a minimum value of the penalty function.

The efficiency of the algorithm of statistic monitoring of the ribbon formation process is estimated using simulation modeling of the system performance with real data collected for the particular production line over a year. The comparative results of modeling the control algorithm for the manual glass ribbon formation process are indicated in Table 2.

The use of the statistic control algorithm ensures high stability of tin temperature over the spans of the float tank. Its application makes it possible to improve the quality of glass by decreasing the mean quadratic deviation of the optical distortions visible in transmitted and reflected light, nonuniform thickness, and the bloom effect. The mean value of the raster, the nonuniform thickness, and the curvature of the glass ribbon decrease simultaneously.

The studies performed have confirmed the possibility of further improving the quality of glass by using mathematical

TABLE 2

Parameter	Manual control		Statistical control algorithm	
	mean value	mean quadratic deviation	mean value	mean quadratic deviation
Bloom effect	1.04	0.10	1.04	0.04
Optical distortions determined by methods:				
"Zebra", deg	63.5	5.2	65.3	3.4
Raster, mm	6.7	3.4	3.3	1.0
Nonuniform thickness of ribbon, mm:				
first segment	0.05	0.05	0.03	0.02
second segment	0.03	0.02	0.02	0.02
Glass sheet curvature, mm	0.03	0.01	0.02	0.01
Tin temperature, °C:				
1st span	1005.5	6.3	1010.7	1.8
12th span	796.0	13.5	793.2	0
20th span	616.1	5.2	604.4	0

models for statistical analysis and control of the process of glass ribbon formation on molten tin.

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